ADSL: a new twisted-pair access to the information highway

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Abstract:

The asymmetric digital subscriber line (ADSL) takes advantage of the existing twisted-pair copper loop that currently provides customer access to the telephone network. An ADSL modem is placed at each end of the loop to create a high speed access link above the existing telephone service. Since ADSL makes use of the existing copper telephone line, its application in the telephone network can conceivably be nearly as ubiquitous as the public telephone network itself. With ADSL, it is possible to connect small numbers of customers to broadband services in areas where full upgrade to hybrid fiber coaxial or fiber facilities is not economical in the near term. ADSL systems offer a means to introduce broadband services using the embedded base of metallic loops in areas where optic fiber-based, hybrid fiber-coaxial radio systems or other broadband transport systems may not be scheduled for deployment in time to meet business needs and customer demand. The article concentrates on ADSL systems capable of at least a nominal 6 Mb/s payload transport toward the customer, in addition to associated upstream channels and symmetrical "telephony" services via nonloaded loops that comply with carrier serving area design guidelines.<>

Subject Terms:

subscriber loops; twisted pair cables; information networks; broadband networks; telecommunication services; twisted-pair access; information highway; asymmetric digital subscriber line; twisted-pair copper loop; telephone network; high speed access link; telephone services; public telephone network; broadband services; hybrid fiber-coaxial radio systems; broadband transport systems; upstream channels; carrier serving area design guidelines; 6 Mbit/s

ADSL: A New Twisted-Pair Access to the Information Highway

ADSL systems offer a means to introduce broadband services using the embedded base of metallic loops in areas where optic fiber-based, hybrid fiber-coaxial radio systems or other broadband transport systems may not be scheduled for deployment in time to meet business needs and customer demand.

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The authors have provided a Glossary of Acronyms which appears at the end of the article.

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Today's media, both the popular and trade press, is buzzing with news bites about the building of a national information infrastructure called the "information superhighway." Telecommunication providers, cable distributors, and a mix of other market entries are busy piecing together their own versions of this infrastructure. Yet, consumers are still uncertain as to how to find an on-ramp, the so called "last mile," that will connect them to the much touted hyperband of hundreds of entertainment sources and interactive capabilities.

Several architectures have been proposed and some are currently being tested in field trials. One of the most popular architectures, due to its relatively low incremental cost per customer, is hybrid fiber coax (HFC), which consists of an optical fiber feed from its network source to a coaxial cable (coax) tied to a few hundred homes. It combines the strength of a high capacity, low loss fiber backbone with the low cost of coax in the last mile to the customer. Another architecture being tried is fiber-to-the-curb (FTTC), which offers significant technical advantages for switched digital services, but has a higher cost per subscriber than HFC. Other promising architectures include 28 GHz wireless and direct satellite, each having its own distinct strengths and weaknesses.

Another architecture is also on the near horizon — asymmetric digital subscriber line (ADSL). This technology takes advantage of the existing twisted-pair copper loop that currently provides customer access to the telephone network. An ADSL modem is placed at each end of the loop to create a high speed access link above the existing telephone service. Since ADSL makes use of the existing copper telephone line, its application in the telephone network can conceivably be nearly as ubiquitous as the public telephone network itself. With ADSL, it is possible to connect small numbers of customers to broadband services in areas where full upgrade to HFC or fiber facilities is not economical in the near term. Its notable advantages are its ease of installation and its portability for use in other locations when the customer requests a disconnect or if a more permanent technology such as HFC is used to replace the existing copper plant. Its limitations center around the number of channels that can be delivered simultaneously to a given customer and, also, the fact that A/D conversion is required to transport analog broadcast channels.

The idea for ADSL was spawned by Joe Lechleider, a Bellcore researcher, in the late 1980s as a natural extension of the digital subscriber line (DSL) access technology developed for basic access (i.e., basic rate) Integrated Services Digital Network (ISDN). Bellcore's computational studies were used by manufacturers and universities in refining the mathematics into working prototypes. (The article on ADSL by David L. Waring and Walter Y. Chen in the May 1994 issue of *IEEE Communications Magazine* provides an excellent tutorial on these topics.) This led to a standards development effort by the ANSI-accredited Committee T1 Telecommunications, sponsored by the Alliance for Telecommunications Industry Solutions (ATIS). The technical development was begun in 1993 in the DSL access Working Group, T1E1.4, of subcommittee T1E1. The first ADSL standard is currently in letter ballot and is expected to be issued in the spring of this year. ANSI has assigned the number "T1.413" to the ADSL standard.

The draft ADSL standard provides for a number of types of payload channels, noted as follows:

- A high speed simplex channel provides a downstream data rate of up to the DS2 rate, nominal 6 Mb/s. The channel can be divided into four 1.5 Mb/s channels, two 3 Mb/s channels, or any other multiple of 1.5 Mb/s rate, provided the total rate does not exceed the maximum rate of 6 Mb/s (The ADSL system can also accommodate payloads composed of European E1 rate, nominal 2 Mb/s, and data streams.).
- A 64 kb/s duplex data payload channel is associated with the high speed channel to allow interactive control and information flow between the

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customer and the information service provider(s). Real time interactive capability is a key aspect of the customer services now being planned.

- Other full-duplex channels provide rates between 160 kb/s and 576 kb/s, depending on the services requested. For example, the customer could order basic rate ISDN and digital telephony at a rate of 384 kb/s; or the customer might order a high speed link at the full rate of 576 kb/s.
- Lest we forget, all of this high speed capability is riding over the 0 Hz (dc) to 4 kHz band allotted to basic telephone service. With the use of filters, ADSL channels and the telephone channel are each oblivious to the traffic in the spectrum above or below their own. Even when an ADSL modem is unplugged, the lifeline basic telephony service is unaffected.

With closure on the letter ballot at hand, the committee already has aspirations for even greater capabilities for the ADSL. Another issue of the standard is being planned that could offer downstream rates as high as the OC1 (51.84 Mb/s) rate and full duplex rates high enough that the name of the new issue has been changed to very high bit-rate digital subscriber line (VDSL). In three short years, the focus has progressed from work on ADSL systems with 1.5 Mb/s payloads in 1993, to 6 Mb/s payloads in 1994, and now to 50 Mb/s in 1995. One limitation on the payload rate is the speed capability of the available digital signal processing in the terminal modems.

The ADSL/VDSL technology is not limited to twisted-wire pairs. Investigations of its applications on coaxial cable and for wireless systems are underway. Since the transmission loss for a given frequency on common coaxial cables is considerably less than for fine gauge twisted pairs, the potential ranges may be even greater. So the ADSL techniques originally conceived for wire pairs may appear in several incarnations in the future of the new information highway.

ADSL's Place in the Broadband Network

ADSL systems offer a means to introduce broadband services using the embedded base of metallic twisted pairs in areas where optical fiber-based, hybrid fiber-coaxial, radio systems or other broadband transport systems may not be scheduled for deployment in time to meet business needs and customer demand. ADSL systems can be applied from the central office to the customer or from a network outside plant multiplexer to the customer.

ADSL systems now in early field trials can transport one NTSC video signal in a compressed digital format. Prototype systems can transport up to four video signals in addition to other digital channels within a digital bandwidth less than 7 Mb/s or an analog bandwidth just over 1 MHz. Advanced ADSL systems that may be capable of transporting 50 Mb/s or more to a useful loop range are the subject of a proposal for a new standards project.

This article concentrates on ADSL systems capable of at least a nominal 6 Mb/s payload transport toward the customer, in addition to associated upstream channels and symmetrical "telephony" services via nonloaded loops that comply with carrier serving area (CSA) design guidelines.[1]

Metallic, Optic Fiber, Fiber-Coax, and Radio Broadband Transport

Optic fiber-based loop access transport systems can deliver gigabits/second of data per fiber. Optic fiber is currently being deployed in the feeder portion of the outside loop plant to supply remote digital loop carrier terminals and SONET multiplexers and Optical Network Unit (ONU) terminals. Large business customers are often fed with optical fibers connecting to the customer equipment.

Emerging coaxial cable systems are potentially capable of 1000 MHz (1 Ghz) of analog bandwidth[2] that can carry a mix of analog and digitally encoded services. Cable TV services are increasingly using optical fiber cable in their feeder system with coaxial cable providing the final customer connection. Coaxial cable is also used for wiring within customer premises for TV and some LAN systems. The current cable TV distribution plant, fiber and coaxial cable, is provisioned for one-way transmission toward the customer. Conversion to two-way transmission is possible for many installations by replacing the system line amplifiers and end equipment.

Terrestrial and satellite radio transmission systems can deliver broadband service to business and residential customers. Most existing entertainment video systems use one-way transmission toward the customer. Proposed radio systems can provide asymmetric two-way transmission with broadband downstream toward the customer and narrowband upstream from the customer. The upstream transmission from the customer is necessary to allow customer interaction with the information source and control of the downstream data flow. In many current cable systems, customer control is via the normal telephone line with a telephone call to a automated service program and human operator backup. Trials of two-way radio systems operating at 28 GHz are currently in progress. Spectrum allocation auctions by the FCC will foster future widespread deployment of radio-based systems.

Except for a few trial areas, the vast majority of residential telephone customers are still served in the "last mile" by copper twisted pair cables. The loop plant has been optimized to efficiently transport baseband analog voice services with less than 3 kHz of bandwidth. Nevertheless, the nonloaded portion[3] of the plant is capable of transporting much greater bandwidth[4] using modern transmission techniques and data compression schemes that can now be implemented with integrated circuits. The portion[5] of the residential customer base now served by bandwidth-limited loaded cable is gradually being replaced by carrier-derived systems with nonloaded loop extensions. In some areas, as much as ten percent of the loop plant has optical fiber feeders to carrier terminals located in the outside plant.

If the proposed 50 Mb/s and up ADSL systems prove practical and economical, the life of

[1] Carrier serving area (CSA) loop design guidelines were originally developed for wire extensions from digital loop carrier remote terminals to customer premises. CSA rules allow up to 12 kilofeet of 24 gauge cable or 9 kilofeet of 26 gauge, less any bridged tap. No more than two gauges of wire are permitted and the total length of bridged tap is limited.

[2] CATV operators are beginning to modernize from the existing 450 MHz systems to 550 MHz, 750 MHz, or higher bandwidth systems. New cable system componenets are often rated for 1 GHz applications.

[3] Historically, 80 percent of the outside loop plant has been "nonloaded" and the longer 20 percent has been "loaded." Inductive loading of a loop results in the loop becoming a lowpass filter with lower loss in the voice frequency range, but a steep cutoff above 3 kHz for the common loading plans. There are also loop loading plans for 7.5 and 15 kHz program audio services.

[4] Transmission loss for nonloaded cables increases approximately as the square root of the frequency.

[5] Individual wire centers vary a great deal from these nationwide averages of 80 percent nonloaded loops and 20 percent loaded loops. Some offices, especially in rural areas, have more loaded cable than nonloaded cable. Digital loop carrier deployment is reducing the use of loaded cable.

the embedded copper loop base could be extended even longer and allow capital investment in advanced transport to be spread out. As more fiber based carrier systems are deployed in the field, the remaining nonloaded cable drops to the customer from the central office or from an ONU are tending to be shorter and shorter. This shorter loop population will help the application of high bandwidth metallic loop transmission techniques.

Video Dial Tone Overview

Figure 1 illustrates a high-level view of an architecture for delivering of video dial tone (VDT) services. At the left are a number of information providers (IP's) (also referred to as information service providers or video information providers). These entities provide interactive customer access to libraries of video, image, audio, and textual information or to televised live events.

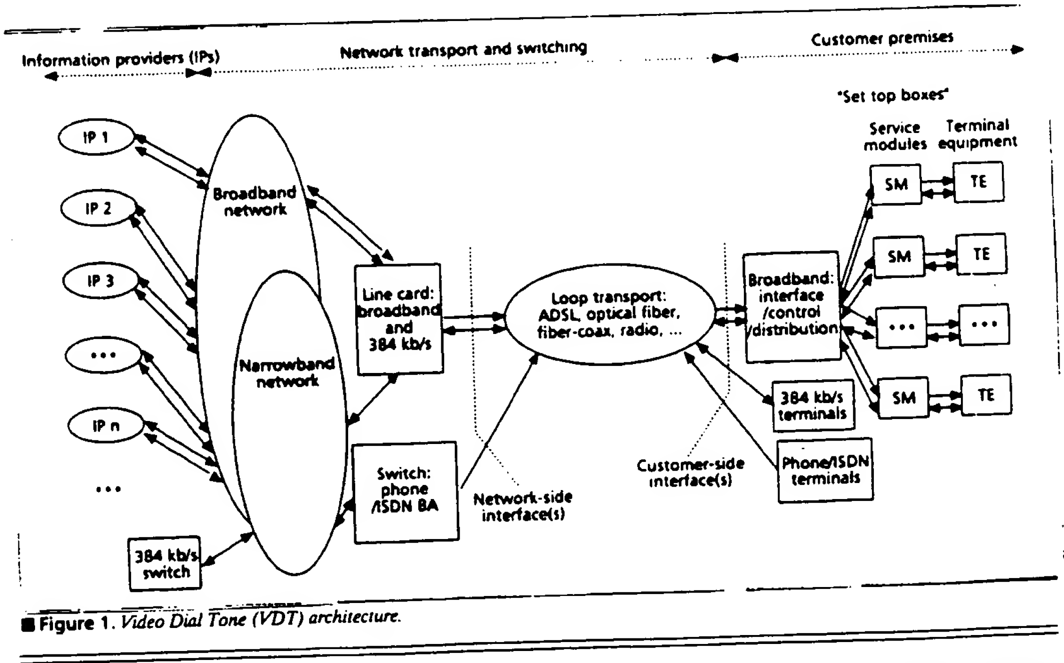
At the right in Fig. 1 is a customer's premises with various terminal equipment such as television sets, video recorders, high-fidelity audio systems, ISDN terminals, workstations, and possibly video conference gear. Also shown are voiceband telephone terminals, such as station sets, fax machines, answering machines, and voice frequency modems. Some of this terminal equipment may interface with service modules (SMs) in ADSL terminology or set top boxes (STBs) in VDT terminology. These SMs contain the specialized decoding, customer-provider interactive control and interface circuits needed to connect with customer terminal equipment for a given service or package of services.

The telephone company network connects the various information service providers and the customers. The main tasks of the network are to move the desired information between the providers and the customer and direct (switch) the information streams as needed. Transport can be:

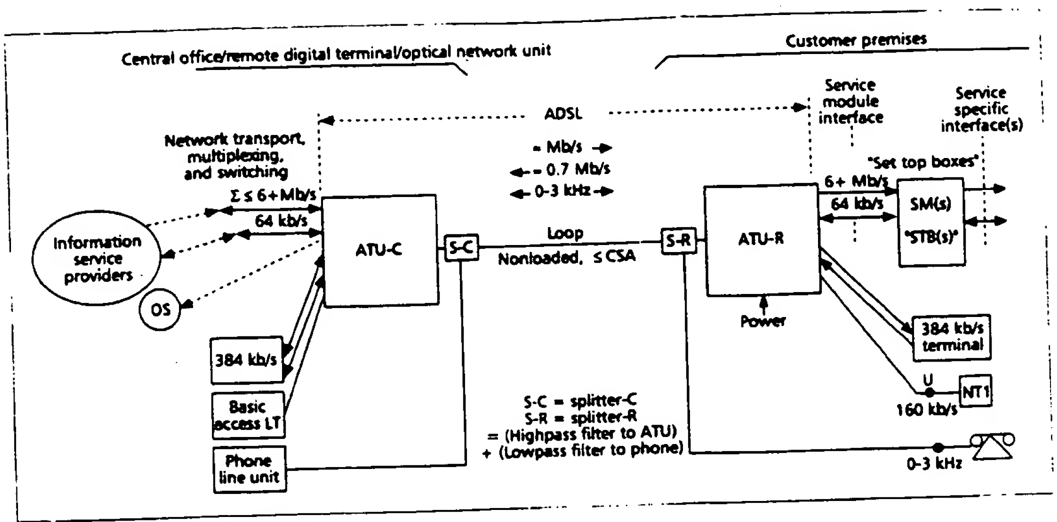
- Point-to-point between a single provider and a single customer.
- Point-to-multipoint between a provider and many customers as in normal broadcast practice via radio or cable.
- Multipoint-to-point between several providers and a single customer location with more than one service active at a given time (i.e., a customer premises with several TV sets, VCRs, or personal computers in use).

The network connects to the information providers via a data transport and switching system that is rapidly evolving from a narrowband, voice-based system to a broadband, digital data system. The network interoffice transport is dominated by optical fiber systems and digital multiplexed transmission. The network also contains the switching and transport elements for traditional telephony services such as basic voice and ISDN Basic Access. The customer's telephony switching services are provided in the nearest network central office. (Not shown are the overlay resources, such as transmission facilities, testing, monitoring and processing equipment, used to provide operations control and maintenance for the overall network and its parts.)

The broadband information service system for entertainment video and audio tends to be highly asymmetric in direction, with the data flow toward the customer being much larger than the flow from the customer toward the network and information provider. A large part of the information toward the customer is expected to be moving image video, while the data from the customer may be low-rate interactive control information such as keypad control for service selection and control



■ **Figure 1.** *Video Dial Tone (VDT) architecture.*



■ **Figure 2.** *ADSL system architecture.*

for entertainment services.

Computer-based services will have file transfers from the customer, but these tend to be smaller than those from the information providers. The information providers and the network provider will transmit graphical menus and interactive responses to the customer. Once a service is selected, service control programming and option selections may sent to the set top box. These customer/provider/STB exchanges can be sent via the low-rate control duplex control channel associated with the wideband channel.

Basic data and voice telephony services that connect customers to other similar customers are designed for the same data transport and switching bandwidth in both directions. Services such as ISDN channels may transport data, video, image, and audio information.

The network and customer meet via the outside loop plant that extends to the central office. The majority of this loop plant is made up of metallic twisted-pair loops designed to optimize analog voice baseband transmission, station set powering and low-frequency call control signaling. An increasing percentage of the loop plant has been replaced with digital multiplex carrier systems with the terminals installed in the outside plant. Digital loop carrier (DLC) systems are used for most of the new and upgraded outside plant installations starting as close as 9 kilofeet (kf) from the central office. Customers served by these carrier systems are connected with metallic loop extensions that tend to be much shorter than those that originate at the central office. Newer carrier system installations are fed by optical fiber transmission systems from the central office. FTTC distribution architectures refer to the remote terminals as ONUs.

While the current narrowband telephony network is optimized for voice switching and transport (in 3 kHz analog and 64 kb/s DS0 digital formats, the newer proposed services require much higher data rates, several megahertz for analog video or several megabits/second for digitized, compressed video. One approach to providing transport of these high data rates through the outside plant to the customer is to install new high bandwidth facilities. Network porivders are planning to serve customers with at least one such facility such as direct optic fiber facilities, coaxial cable, or microwave radio transmission. It will be years before a significant fraction of the customer base can be served with new facilities. Another approach is to utilize advances in integrated circuits, transmission techniques, and data compression algorithms to develop transmission systems that extend the useful bandwidth and economic service lives of the embedded copper loops. ADSL technology is such a system.

ADSL System Architecture

Figure 2 illustrates the basic architecture of an ADSL system. The ADSL functions at the network end (or central office end) are labeled ADSL Terminal Unit-C (ATU-C)[6] together with a splitter function (S-C). Splitter-C may be packaged with the ATU-C. The ADSL functions at the customer end (or remote end) of the loop are labeled ADSL Terminal Unit-R (ATU-R) together with a splitter function (S-R). Splitter-R may be packaged with the ATU-R. The ATUs contain the necessary loop transceivers (modems), multiplexing system, and individual terminal unit control. The splitters serve to direct the ADSL signals (above about 20 kHz) and basic voice and control telephony signals (below 4 kHz) to and from the loop and to isolate one set of signals from the other. Reasonable passive filter designs necessitate a guard band from 4 to 20 kHz between the voiceband and ADSL signals.

The ATU-C interfaces with the network switching, transport, and other multiplexing functions and network operations. It may be located in a central office or in a remote hut in the outside plant as an extension of a carrier system. The ATU-C performs the basic multiplexing, demultiplexing, transmitting, receiving, and system control functions

[6] *In ADSL and HDSL terminology, the suffix "-C" indicates a device used at the central office or network end of the system. The suffix "-R" indicates a device used at the "remote" or customer end of the system.*

The network is in the midst of an evolution from the traditional digital transmission hierarchy to one built on ATM that has very little restriction on channel bandwidths.

and provides interfaces to the loop, network transport, and switching and operations systems (not shown). The ATU-C functions might also be integrated within a higher level network element, e.g., a carrier multiplex terminal such as a DLC remote digital terminal (RDT), fiber ONU, or ATM multiplexer. The Splitter-C forms the interfaces among the ADSL transceiver in the ATU-C, the voice telephone network, and the loop.

Connecting the network and the customer premises is the twisted-pair copper loop. Figure 3 depicts a possible set of the spectra on the loop for echo canceller with hybrid (ECH) ADSL system. There are the bidirectional basic voice telephony signals, the downstream ADSL signal with a binary equivalent bandwidth in the 7 Mb/s range, and an upstream ADSL signal with a binary equivalent bandwidth in the 700 kb/s range. The analog bandwidths for the ADSL signals depend on the modulation scheme used, but are probably about 1 MHz downstream and about 100 kHz upstream.

The T1E1.4 ADSL interface standard allows both ECH and frequency division multiplexing (FDM) bandpass structures for ADSL system implementations. The two types would be able to interoperate with an ECH ATU recognizing and adapting to the frequency bands of a connected FDM ATU. Echo canceller implementation allows the ADSL loop spectra to be kept as low as practical in frequency to minimize loss and possible radio interference at the cost of increased complexity.

The most convenient description for the target loop population that is desired for ADSL system deployment are the CSA guidelines originally developed for DLC system loop extensions. For ADSL system deployment purposes, the description is also applied to loops that originate from the telephone company central office even though there is no loop carrier system involved. The intent is that loop serving areas in which the loops comply with CSA rules. ADSL systems may be installed without loop conditioning, such as removal of bridged taps. Pre-service testing of the individual loops is not needed. Actual CSAs associated with DLC systems have been designed to comply. For the areas around a central office, most loops can be screened and qualified in bulk from the plant records. Individual nonloaded loops that do not comply with CSA guidelines may still work for ADSL transmission, but a concise characterization is not available and full ADSL system performance is not guaranteed.

A Splitter-R function forms the interfaces among the loop, ADSL transceiver in the ATU-R, the telephone internal premises wiring, and terminals. The ATU-R presents the interfaces to the local distribution for the broadband services via the SM/STB. The ATU-R also presents customer interfaces for ISDN Basic Access, either "U" (shown) or "S/T" (not shown), and any 384 kb/s or 576 kb/s-based services that are present. Note that the ATU-R requires local powering at the customer premises because the basic telephone direct current on-hook/off-hook signaling and station set powering takes precedence.

The STBs contain the necessary decoders and terminal interfaces for the given service and customer control interfaces. A given ATU-R may feed one or more STBs.[7]

Each of the ADSL receivers in the ATU-C and in the ATU-R can relay information back to its companion transmitter at the other ATU via the transmitted channel in the opposite direction. These information feedback paths allow each transmitter to adapt sub-channel bit capacities and power allocations to the loop characteristics and interference as measured by its companion receiver.

ISDN Basic Access may use either a two-wire "U" interface or a four-wire "S/T" interface at the customer's choice. The ATU-R should be able to recreate either the 160 kb/s 2B1Q DSL signal for the U interface, or the 192 kb/s for the S/T interface depending on the customer needs.

ADSL-3 With Synchronous and Asynchronous Networks

The telephone network is in the midst of an evolution from the traditional digital transmission hierarchy built on DS0 (64 Kb/s) and DS1 (1.544 Mb/s), or E1 (2.048 Mb/s in Europe and elsewhere) modularities to one built on asynchronous transfer mode (ATM). ATM may use channel bandwidths that are multiples of 4 kb/s for convenience in generating clocks. The existing digital hierarchy is now being retroactively referred to as "synchronous transfer mode" (STM).[8]

SONET virtual tributaries can transport broadband channels that will become the ADSL payloads. SONET VT1.5, VT3, and VT6 payloads correspond to the DS1, DS1C, and DS2 data rates of 1.544, 3.152, and 6.312 Mb/s, respectively. SONET can also carry ATM cells which can accommodate data rates with fine increments.

The proposed ADSL-3 system framing structure is capable of allocating its downstream and upstream payloads in increments of 32 kb/s. ADSL systems can accommodate traditional digital rates, both US and European, as well as ATM-based payloads.

T1E1.4 Draft Interface Standard

The first complete draft version of the ATIS (formerly ECSA) Working Group T1E1.4 draft ADSL interface standard was assembled at the June 6-10, 1994 meeting in Kansas City, Missouri. Disposition of all comments on issue 1 was reached at the February 27-March 1, 1995 meeting. T1 Committee approval is expected to be automatic. ANSI publication of the document will likely be by summer 1995.

The Working Group has chosen to emphasize Discrete Multitone (DMT) implementations over other proposals such as quadrature amplitude modulation (QAM) or carrierless AM/PM (CAP). As previously mentioned, the standard allows both ECH and FDM implementations. Most of the desired features and expected performance of an ADSL system are not dependent on having a specific transmission scheme.

The standard allows two levels of capability: Category I or "basic" and Category II or "enhanced." Category I has "sub-CSA" loop range, does not require trellis coding and allows either ECH or FDM.

[7] A recent proposal for a customer premises distribution architecture has multiple ATU-R and SM/STB pairs fed by a single ATU-C at the network end, thus providing a point-to-multipoint structure.

[8] Similarly, the term "Plesiosynchronous Digital Hierarchy" (PDH) has been coined and used to refer to the traditional digital transmission network to distinguish it from the SONET/Synchronous Digital Hierarchy (SDH).

Category II has full CSA-type loop coverage as a target and requires echo cancellation.

Among the many system issues addressed in developing the ADSL standard were:

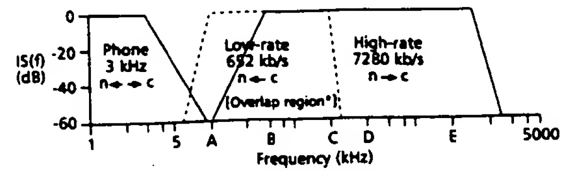
Spectrum Compatibility — Spectral compatibility and mutual crosstalk among ADSL systems and the many transmission systems already in use in the outside loop plant. Analysis of the interaction between ADSL signals and the DS1 T-carrier lines, resulted in spelling out deployment guidelines for ADSL depending on whether T-carrier was present and whether the two systems shared the same binder group.

Impulse Noise — Impulse noise has not appeared to be a significant performance impairment for DSL, HDSL, or T1 line systems. However, the received signal levels for ADSL systems, especially at the customer end for the high frequency downstream signal, are much lower than for earlier systems. Until recently, little experimental data was available on the statistics of sources, levels, waveshape/spectra, and arrival times for impulses at the customer premises. The existing data did indicate that the impulse levels were on the same order as ADSL signals and the spectra overlapped. Thus, the potential for ADSL system transmission errors was significant. ADSL system designs include forward error correction and coding schemes to counteract the burst error effects of noise impulses. Data from recent customer premises impulse noise measurements are being used to help develop simulations and laboratory performance verification tests for impulse noise. The ADSL draft standard includes a laboratory impulse noise test.

ADSL Versus Telephone Service — Mutual effects between ADSL transmission and the telephone voice and control signaling that share the same host loop were the focus of intense study.[9] Indeed, the most fundamental ADSL system requirement is to hold degradation of telephone transmission and operations to an absolute minimum level. The standard specifies maximum values for additional dc resistance, voice frequency loss, and frequency distortion and return loss/impedance degradation.

Radio Frequency Interference — Although not specifically addressed in the standard, potential radio frequency interference from ADSL signal radiation leakage from the loop and inside wiring. There is also a potential for interference to ADSL transmission from radio energy coupling into the loop from external sources. Bellcore analyzed both cases considering the many radio services, including AM broadcast band, which overlap the ADSL frequency spectrum. The results were submitted to the Working Group. It appears that as long as accepted practices for maintaining electrical balance between each of the two loop conductors, and the connecting circuitry and the external environment are followed, there should be minimum concern for radio frequency interference.[10]

The standard devotes several pages to describing the many possible payload channelization options to accommodate common U.S. and European data rates.



n → c, n ← c, n↔c = "network" and "customer" directions

"A, B, C, D, and E" = relative increasing frequencies

*Possible spectrum overlap between transmission toward the customer and from the Echo cancellation will allow such operation.

The "high-rate" (toward the customer) and "low-rate" (toward the network) data rate values shown are illustrative examples that allow for ADSL system overhead functions such as framing, operations communications, and error control above the payload data rates.

■ **Figure 3.** *Example of ADSL-3 spectra with echo cancellers.*

ADSL Forum

A new organization, the ADSL Forum, has just formed to deal with market and technical issues for ADSL system deployment. The ADSL Forum is patterning itself after the ATM Forum, which is playing a key role in ATM development and deployment. The ADSL Forum has the goal to push forward on all aspects of ADSL deployment. There is a Marketing/Services/Educational subgroup and a Technical subgroup. A prime mission of the Marketing group is to influence affected company executives, in the United States and around the world, that ADSL makes sense until HFC and FTTC can be deployed. The technical subgroup intends to pick up where the standards groups like T1E1.4 and ETSI leave off and ensure that complete end-to-end network solutions are available for ADSL deployment. They plan to establish links to the network providers, equipment vendors, and all of the related standards bodies, forums, user groups, and other entities related to broadband services.

The ADSL Forum technical subgroup plans to publish proposals for networking solutions for ADSL deployment as they are developed. They plan to address most of the unanswered concerns mentioned elsewhere in this document.

Additional Network Provider Requirements

A new technology should merge smoothly into deployment in the telephone network and provide reliable, economical service. For this to occur, it is not enough to have a standard specification for the electrical and physical details of the network to customer interface. Beginning with an interface standard, the network providers supplement such specifications with additional requirements. Among the subjects covered are: operations, administration, provisioning and maintenance (OAM&P), network synchronization, physical design and packaging, powering, environmental and safety concerns, human factors, equipment identification, documentation, personnel training, manufacturing, and quality control. These supplementary requirements may be published in the form of Bellcore documents, network provider request

[9] *A charter function of the T1E1.4 working group is to develop interfaces associated with network-customer access. In order to do that, the standards document explores the implications of the interface both into the network and into the customer premises. It had to also consider any possible effect on telephone performance and operations.*

[10] *For the advanced very high rate systems, this issue will probably require another look. Radiation efficiency increases as signal wavelengths decrease and become comparable to loop segment lengths.*

for quotes (RFQ), and references to requirements and standards by other industry and standards entities such as the IEEE, ISO, and ANSI. The vendors, networks, and Bellcore work together to develop systems that meet network needs while balancing costs and allowing for equipment designer innovation. Some of the tradeoffs for ADSL systems are discussed below.

Spectrum Compatability, Loop Population, Line Rate

ADSL system bandwidth capacity and transmission range must be traded off against each other. The first desire is to have the system capacity, and thus the line rate, be as high as the technology allows. Likewise, the desire is to cover as much of the loop population as possible, such as all of the nonloaded loops. Unfortunately, the worst case "legal" loop can not support the maximum possible line rate and remain spectrally compatible with other ADSL systems or other transmission systems that may be in the same cable.

At a given time, the state of the art in digital signal processing gives some limit on the possible transmission line rate. Transmitter circuit linearity, and spectrum compatibility concerns place bounds on the transmitter power that can be used on the loop. With a bound on power, the loop loss versus frequency characteristics result sooner or later in received signal levels low enough that they can not be extracted from the background noise on the loop or internal receiver noise without increasing the complexity and cost or delaying availability of the system beyond the market predictions and needs.

Operational and administrative concerns are as important as the transmission characteristics of the loop plant. The operating company must be able to readily identify the subset of the loop population on which an ADSL system will operate the vast majority of the time (say, for example, 95 percent with some performance criterion such as bit error ratio (BER) less than 10^{-7}) without qualification testing of the individual loops. The operational support data bases must have flags for serving areas that ADSL systems can be installed with assurance that almost all will work without modifications of the loop. Nonloaded loops are flagged in the data bases. A computerized operations system (OS) can possibly be used to help identify a serving area in which the loops conform to CSA rules or distribution area (DA). Bulk qualification of loops by serving area is highly preferable.

Some ADSL systems were developed and put into production before the ADSL standards was developed. These systems can transport a 1.5 Mb/s payload through 18 kf nonloaded Resistance Design loops.[11] With MPEG-1 video compression, 1.5 Mb/s provides video quality that is perceived to be equivalent to VHS VCR. These 1.5 Mb/s systems are being used for field trials.[12]

The focus of the standard is an ADSL system that is capable of transporting 6+ Mb/s digital signal through CSA-type loops without T1 carrier present or through Distribution Area type loops with T1 present. With MPEG-2 compression, a 5 to 6 Mb/s signal can provide video that is perceived as full-motion studio NTSC quality.[13] Alternatively, the 6 Mb/s stream may be composed of one or more 1.5 Mb/s video streams, or higher rate data streams with a total of about 6 Mb/s.

Transmission Delay

Voice communication and real time duplex services tend to be intolerant of transmission delay beyond a very few milliseconds unless special circuit designs with echo suppression or echo cancellation or delay tolerant communications protocols are provided. Even with delay treatment, delays above some fraction of a second result in human communication becoming awkward. For data communications, protocols must allow for extended round-trip delay. Fortunately, these services tend to be more tolerant of errors.

Motion video, high quality audio or image services with broadband transmission toward the customer, and an associated narrowband duplex control channel can be very tolerant of transmission delay. For most services, a one-way delay of a second or more on the downstream broadband channel probably would not affect customer satisfaction. For the duplex control channel,[14] delays of small fractions of a second should not be noticeable to the customer.

Broadband video services tend to be much less tolerant of errors than services such as voice or narrowband data. A bit error ratio that would be not noticed on a voice channel can result in totally unacceptable artifacts in video transmission. For that reason, error control is embedded in the encoding and compression algorithms for video. For transmission errors that the receiver cannot correct, error concealment techniques, such as continuing to present the last "good" screen image, are utilized. As discussed, in addition to the error control within the broadband payload, ADSL systems are expected to need their own error control to achieve acceptable performance for the candidate services with the impairments and interference in the loop environment.

Candidate services that tend to be intolerant of errors tend to be tolerant of the transmission delay introduced by error control techniques. Services that tend to be relatively tolerant of errors tend to be intolerant of transmission delay. The ADSL standard allows for payloads to be assigned to either error-protected paths with added delay or to minimum delay paths through the ADSL system as appropriate.

Remaining Issues for ADSL Deployment

There are a number of issues about deployment of ADSL-type systems for which complete answers are not yet available:

- How can ADSL systems accommodate transport of existing analog broadband services, such as non-premium television channels, without requiring a STB for each customer terminal.
- How can ADSL systems allow for the graceful evolution from ADSL system installations to possible future hybrid fiber-coax or optic fiber upgrades of the outside plant?

[11] Two Bellcore Framework Advisories, FA-NWT-001307 and FA-NWT-001308, discuss preliminary views of basic technical and operational considerations and requirements for 1.5 Mb/s systems.

[12] Such pre-standard 1.5 Mb/s ADSL systems are often called "ADSL-1" systems as the first generation. These systems are being considered as access vehicles to the Internet since they have a transport capacity much larger than current 28.8 kb/s analog voiceband modems.

[13] The current MPEG-2 video compression standard needs about 20 Mb/s for high-definition television (HDTV). High-rate HDTV-capable ADSL systems have been proposed. The need for long loop coverage should decrease as optical fiber feeder transport systems are deployed both closer to the central office and to the customer. The T1E1.4 Working Group is seriously considering starting a study project on very-high-rate DSL (VDSL) systems that will consider both asymmetric and symmetric transport for payloads of at least 51.84 Mb/s. ETSI is also considering high rate DSL systems. Other industry entities are considering similar rate systems for local area network applications.

[14] Processing at the service provider end may be the dominant delay for the control channel.

- How can ADSL systems be provisioned without individual customer service design or loop conditioning? How robust is the ADSL system to: loop structure conditions, such as working lengths or bridged taps longer than indicated by records; common loop faults, such as corrosion or water incursion; interference from other systems, such as 1.5 Mb/s T1 lines.
- How can advanced high rate DSL systems be deployed while minimizing radio frequency interference concerns?

Each of the broadband transport architectures have their own list of concerns.The relative importance of some concerns depend on the application; for example, transport of analog television channels is not critical to computer-based services. These issues are now being addressed by the ADSL Forum and others.

Where Do We Go From Here

A The role that ADSL will have in providing access to the information highway is still being formed by industry, network trials, market strategies, and the rapidly increasing ADSL payload capacity. Some believe that the greatest asset of ADSL technology is its ease in providing business and learning applications, such as work-at-home, LAN interconnection, distance learning, and, perhaps more importantly, Internet access. Others are hanging their hats on providing access to entertainment sources such as movie, educational, and lifestyle libraries.

Some people are not yet sure about ADSL's place in broadband transport deployment. Questions center around the diversion of scarce resources from new HFC deployment, thus penalizing the solution of choice by many industry experts. Yet others in the industry foresee a synergy of ADSL with HFC (and also FTTC). ADSL, they believe, will allow them to attract larger audiences by providing nearly ubiquitous access to the information highway in the near term. With their ability to share an existing host twisted pair copper loop with an ordinary telephone service, ADSL systems provide the network operators a means to offer wide bandwidth services in customer areas where the initial demand is relatively low and scattered. When HFC or FTTC does become economically attractive in those areas, ADSL modems can easily be removed and reused elsewhere. As mentioned, ADSL systems could be used as one type of extension of FTTC to the customer premises. The tactic of reusing interim solutions, by the way, is currently being employed with a sister technology, high-bit-rate digital subscriber line (HDSL). HDSL modems are used when neither T1 carrier nor fiber is available to provide 1.5 Mb/s DS1-based services on a timely basis. Provisioning HDSL, as expected for ADSL systems, is quick, with no system adjustments and no changes in the loop. When fiber becomes available in that customer area, the HDSL electronics are recovered and used elsewhere.

Whatever services ADSL technology will ultimately support, whether they be business, entertainment, or both, is yet to be realized. Being able to convert an existing copper access line that was designed for voice access into a multimegabit digital access ramp to the information highway is an intriguing and exciting thought for industry and users alike.

ADSL technology is a synergistic complement to HFC and FTTC broadband deployment.

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Glossary of Acronyms

ADSL — asymmetric digital subscriber line: DSL with higher bandwidth capacity in one direction, usually toward the customer.

ADSL Forum: organization formed to promote ADSL system deployment and to act as a central focus for addressing ADSL concerns.

ANSI — American National Standards Institute: accredits ATIS (formerly ECSA) to develop network-customer interfaces.

ATIS — Alliance for Telecommunications Industry Solutions: supplants Exchange Carriers Standards Association (ECSA) as sponsor of T1 Working Groups (1993). See also ANSI, ETSI.

ATM — asynchronous transfer mode: digital switching of one fixed length 53 byte cell at a time.

ATM Forum: organization formed to promote ATM deployment and to act as a central focus for addressing ATM concerns.

ATU-C — ADSL Terminal Unit-Central Office: ADSL terminal nearer to network at central office or remote network node.

ATU-R — ADSL Terminal Unit-Remote: ADSL terminal nearer to customer.

CAP — carrierless amplitude modulation/phase modulation: a candidate technology for ADSL; a passband transmission technique; a variant of QAM. Current standards committee emphasis is on DMT.

CO — central office: refers to a switching entity for an NXX code, the first three digits of a local phone number. The term "wire center" is used to refer to the building when referring to the origin of the outside loop plant. Sometimes "central office" is used to mean "wire center" when the intent is clear. A wire center often has more than one central office NXX code.

CSA — carrier serving area: loop design guidelines developed for wire extension from DLC RDTs to customer premises. Allows maximum of 12 kf/24 gauge or 9 kf/26 gauge, less any bridged tap. Additional rules limit the use of mixed gauges and the total length of bridged tap. A CSA may contain one or more distrubtion areas (DAs).

DA — distribution area: loop distribution area beyond outside plant distribution interface.

DLC — digital loop carrier: an enhanced variety of digital channel bank that allows one end, the remote digital terminal (RDT), to be installed in the outside plant.

DMT — Discrete Multitone: a version of multi-carrier modulation that allows allocation of payload data bits and transmitter power among more than one subchannel depending on the loss, impairments and interference encountered for each subchannel. Individual subchannels may use QAM (or other modulation). Can be set up for baseband or passband. A candidate technology for ADSL. Current ANSI ATIS standards committee emphasis is on DMT techniques.

Drop wire: last portion of loop connecting distribution cable to the customer premises; the most common single-pair aerial drop wire (F-type) has parallel conductors, not twisted.

DS0 — digital signal 0: 64 kb/s. Used for the traditional 8 bit PCM voice channel.

DS1 — digital signal 1: 1.544 Mb/s with a payload of 1.536 Mb/s. Bidirectional. ADSL uses only one direction. European counterpart is E1 at 2.048 Mb/s.

DS1C — digital signal 1C: 3.152 Mb/s. Can transport two asynchronous DS1s by bit-stuffing.

DS2 — digital signal 2: 6.312 Mb/s. Can transport four asynchronous DS1s.

E1 — 2.048 Mb/s: European counterpart to DS1 1.544 Mb/s signal. Uses a common signaling channel for customer signaling instead of robbed-bit signaling. The E1 payload is 1.984 Mb/s.

EC — echo cancellation: a technique for implementing a DSL in which a record of the transmitted signal is used to remove echoes of this signal that may have mixed with and corrupted the received signal. It allows the transmitted and received spectra to be the same or to overlap on the same media at the same time.

ECH — echo canceler with hybrid: used for DSL and HDSL systems and possibly for later generation ADSL systems such as ADSL-3.

ETSI — European Telecommunication Standards Institute: European counterpart to ANSI ATIS (formerly ECSA) in developing telecommunications standards.

FEXT — far-end crosstalk: crosstalk in which the interfering circuit and the interfered circuit are both transmitting in the same direction with overlapping spectra. The disturbed receiver is at the far end of the media from the disturbing transmitter. FEXT is a performance limiter for ADSL systems on twisted pairs.

FTTC — fiber-to-the-curb: fiber to a remote electronics node close to the subscriber (curbside), referred to as an Optical Network Unit (ONU).

ISO — International Standards Organization:

LT — line termination: termination for an ISDN Basic Access DSL at the exchange termination (ET).

MPEG — Moving Picture Experts Group: an ISO standards group working on digital data compression algorithms for storage and transmission of high quality full-motion video with associated audio and data channels. ISO standard 11172.

MPEG-1 — First phase standardization effort on compression encoding up to 1.5 Mb/s total for "VHS (VCR) quality" video and audio channels. Audio at 64, 128 or 192 kb/s per channel. DCT-based algorithms.

MPEG-2 — Second phase standardization effort encoding. Includes NTSC and HDTV with rates from 2 to at least 20 Mb/s. For higher "broadcast" quality and motion video with associated audio and data channels.

NEXT - near-end crosstalk: crosstalk in which the interfering circuit and the interfered circuit are transmitting in different directions with overlapping spectra. The disturbed receiver is at the same (near) end of the media as the disturbing transmitter. Tends to be a performance limiter for symmetric DSL systems. See also FEXT.

NT, NT1 — network termination: ISDN; NT1 terminates layer 1 functions only.

OAM&P — operations, administration, maintenance, and provisioning.

OS — operations system: computer-based management/data base system for one or more aspects of OAM&P.

RDT — Remote Digital Terminal: DLC or IDLC terminal located in the outside plant nearer to customer than COT. See also COT, DLC.

RFI — radio frequency interference: an electronic system either being interfered with by another radiation source or the system interfering with another system.

RFQ — request for quotation: document requesting product pricing and availability information from potential suppliers. May include desire product specifications.

SM — service module: module that converts ADSL payloads to/from customer specific service interface(s). See also STB.

SONET — Synchronous Optical Network: plan for synchronous multiplexing for optical fiber transport. Accommodates both synchronous and asynchronous payloads. Signals are multiples of OC-1 = 51.84 Mb/s. OC-3 = 3 x 51.84 = 155.52 Mb/s. European version is Synchronous Digital Hierarchy (SDH). See also OC-*n*, PDH, STS-*n*, SDH.

STB — set top box: device that performs payload decoding and electrical, physical, and control interface functions for broadband services. See also SM.

STM — synchronous transfer mode: new term for traditional TDM switching to distinguish it from ATM. See also ATM.

TE, TE1 — terminal equipment, type 1: ISDN customer premises equipment.

VDSL — very-high-rate Digital Subscriber Line: DSL capable of transporting 50 Mb/s payloads or greater, either symmetric or asymmetric.

VT — virtual tributary: SONET channels defined to transport traditional digital hierarchy signals. VT1.5, VT2, VT3, and VT6 can carry payloads of DS1 (1.544 Mb/s), E1 (2.048), DS1C (3.152), and DS2 (6.312), respectively.